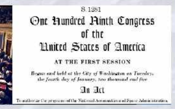
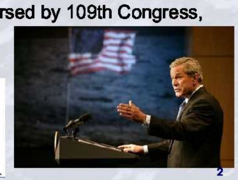
The Moon is a Planet Too: Lunar Science and Robotic Exploration

Dr. Barbara Cohen
Planetary Scientist
NASA Marshall Space Flight Center
Huntsville AL 35805 USA
Barbara.A.Cohen@nasa.gov

U.S. Space Policy (VSE)

- Conceived in response to loss of Columbia Shuttle, 2003
  - Return Shuttle to flight
  - Complete ISS assembly and retire Shuttle
  - Build new human spacecraft for transport beyond LEO
  - Return to the Moon with people and robots to explore and prepare for voyages beyond
  - Human missions to Mars and other destinations
- Proposed by President Bush, endorsed by 109th Congress, now national policy


S.1281
One Hundred Ninth Congress
of the
United States of America
AT THE FIRST SESSION
An Act

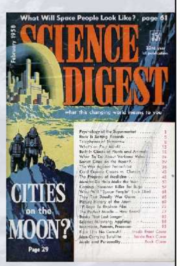


2

Wait – haven't we been there, done that?

- Yes, we've been there – but we haven't done that!

Lunar Exploration
We'll learn to live and work on another planet



Lunar Science
The Moon is a window back in time to understand how all rocky worlds formed and evolved

3

Going back to the Moon for science

- Lunar science through Apollo 17 told us about commonality of planets and uniqueness of the Moon
- Now we have many questions about how planets work that can be answered on the Moon
- We know more about Mars than we do about the Moon in some ways!

	Mars	Moon
Best orbital resolution	2 cm/px (HiRISE camera on Mars Reconnaissance Orbiter, 2005)	50 cm/px (LROC camera on Lunar Reconnaissance Orbiter, 2009)
Topography and Gravity	37 cm vertical, 330 m horizontal (MOLA on Mars Global Surveyor, 1999)	100 cm vertical, 100 m horizontal (LOLA on Lunar Reconnaissance Orbiter, 2009)
Robotic rovers	Pathfinder, Spirit, Opportunity, MSL	Russian Lunakhod-1 and Lunakhod-2
Landing site coverage	Global (east/west, equatorial/ polar)	Limited (nearside equatorial only)

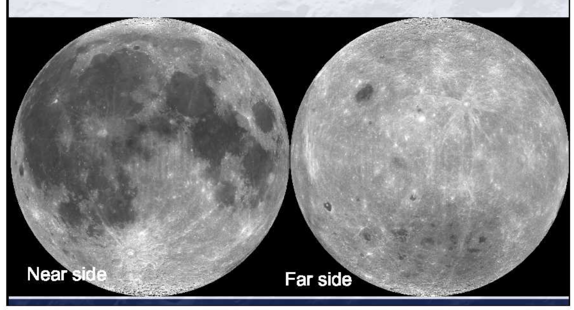
4

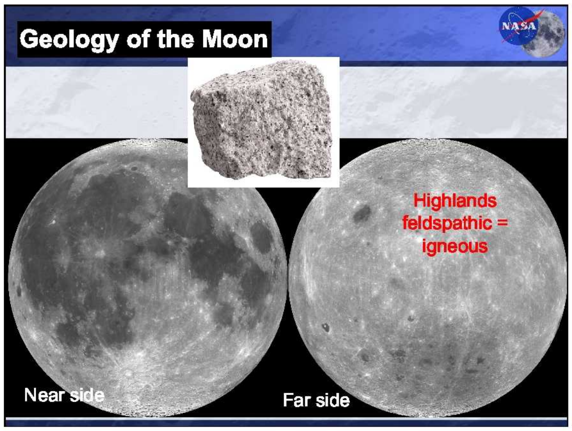
The Moon is a terrestrial planet

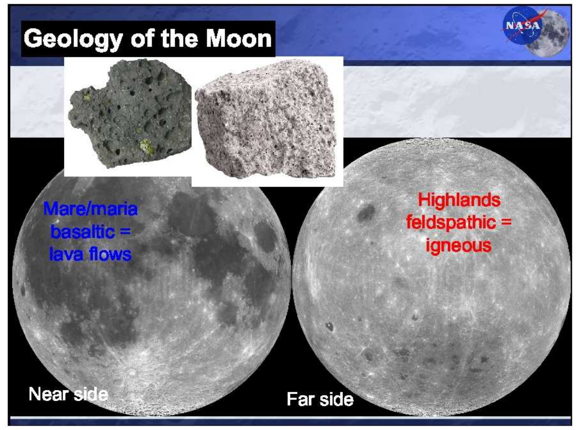
- The Moon holds a unique place in the evolution of rocky worlds - many fundamental concepts of planetary evolution were developed using the Moon
- The Moon today presents a record of geologic processes of early planetary evolution:
  - The Moon and Earth are related and formed from a common reservoir
  - Lunar interior retains a record of the initial stages of planetary evolution
  - Lunar crust preserves ancient crater record, unaltered by plate tectonics (Earth), planetwide volcanism (Venus), or wind and water (Mars & Earth)
  - Surface exposed to billions of years of interplanetary inputs

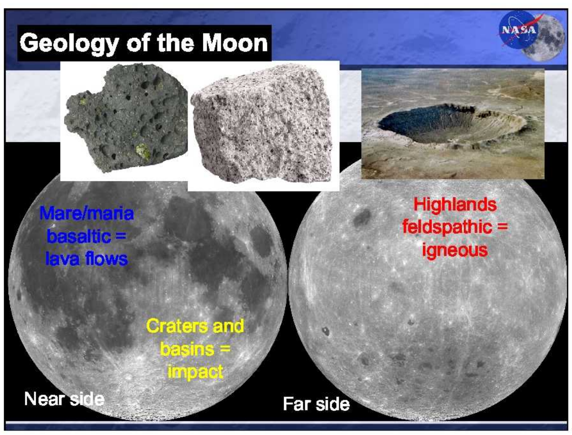
5

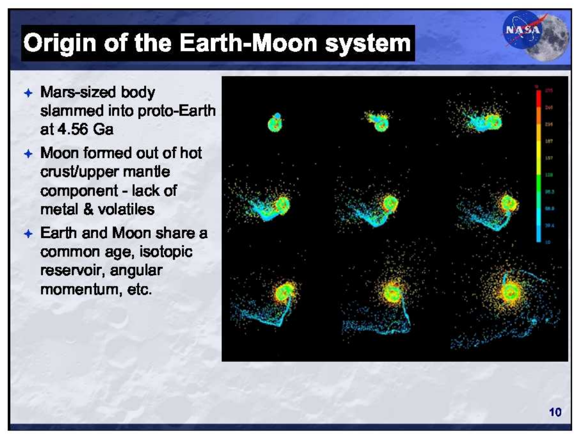
Geology of the Moon

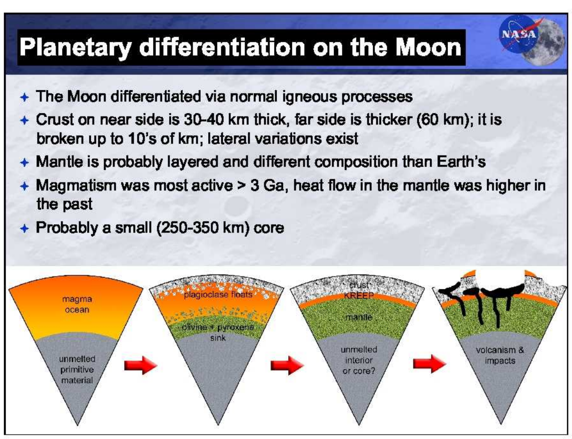


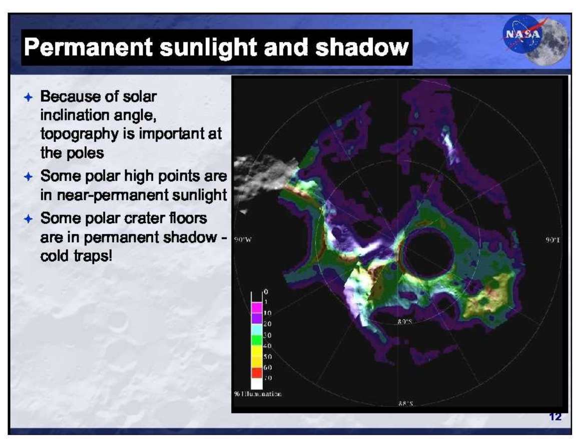

Geology of the Moon
Highlands feldspathic = igneous
Near side
Far side


Geology of the Moon
Mare/maria basaltic = lava flows
Highlands feldspathic = igneous
Near side
Far side


Geology of the Moon
Mare/maria basaltic = lava flows
Highlands feldspathic = igneous
Craters and basins = impact
Near side
Far side

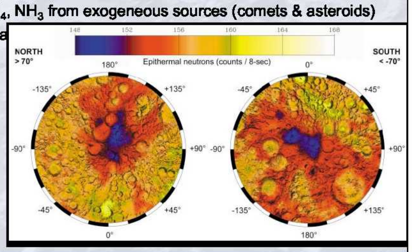

Origin of the Earth-Moon system
+ Mars-sized body slammed into proto-Earth at 4.56 Ga
+ Moon formed out of hot crust/upper mantle component - lack of metal & volatiles
+ Earth and Moon share a common age, isotopic reservoir, angular momentum, etc.
10


Planetary differentiation on the Moon
+ The Moon differentiated via normal igneous processes
+ Crust on near side is 30-40 km thick, far side is thicker (60 km); it is broken up to 10's of km; lateral variations exist
+ Mantle is probably layered and different composition than Earth's
+ Magmatism was most active > 3 Ga, heat flow in the mantle was higher in the past
+ Probably a small (250-350 km) core
magma ocean
unmelted primitive material
plagioclase floats
olivine + pyroxene sink
crust
KREEP
mantle
unmelted interior or core?
volcanism & impacts


Permanent sunlight and shadow
+ Because of solar inclination angle, topography is important at the poles
+ Some polar high points are in near-permanent sunlight
+ Some polar crater floors are in permanent shadow - cold traps!
12

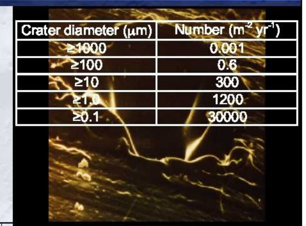
Lunar atmosphere and cold traps

- Surface-bound exosphere, common to airless bodies
  - Ne, He,H from the solar wind
  - Ar outgassing from lunar interior (decay of K)
  - Na, K, ballistic particles liberated from silicates
  - H_2O, CO_2, CH_4, NH_3 from exogeneous sources (comets & asteroids)
- Clementine and ea
- LCROSS will measure water content



A free surface in interplanetary space

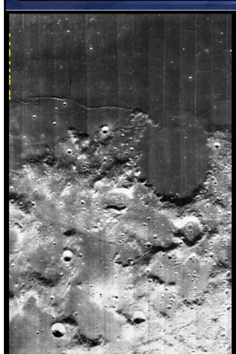
- The lunar surface interacts directly with the interplanetary environment
- Records the current and ancient plasma environment, solar wind, micrometeoroid flux, magnetic fields, etc.



Crater diameter (μm)	Number (m^{-2} yr^{-1})
≥1000	0.001
≥100	0.6
≥10	300
≥1.0	1200
≥0.1	30000

	Energy (MeV/nucleon)	Flux (cm^{-2} s^{-2})	Penetration depth (cm of Al)	Max dose
Solar wind	10^{-3}	10^{8}	10^{-6}	0
Solar energetic particles				
Protons	1 to 10^{3}	$<10^{5}$	1 to 10^{2}	<10 Gy
Helium nucleii	1 to 10^{3}	~1%	1 to 10^{2}	~1%
Galactic cosmic radiation				
Protons	10^{2} to 10^{4}	2	1 to 10^{3}	0.02 Sv/yr
Heavy nucleii	10^{2} to 10^{4}	0.2	10^{-1} to 10^{2}	0.23 Sv/yr

Craters of the Moon



- The Moon is the only place that links relative ages (crater counting) with absolute ages (samples)
- Forms the basis for all other surfaces (Mars, Mercury, etc)
- Bombardment history of the Moon is magnified on the Earth

The Lunar Cataclysm Hypothesis

- An anomalous period of increased bombardment around 3.9 Ga – 600 Myr after solar system formation
- A post-Apollo view of a dynamic solar system
  - Precise ages of impact-melt samples
  - Large numerical simulations of planet formation & migration
- ***Catastrophe*** – 1,700 craters on the Moon / 22,000 impact craters on the Earth
- ***Catalyst*** – delivery of 1023 g of asteroidal/cometary material to the Earth, including C, H2O, and reduced species
- ***Cauldron*** – impact-generated hydrothermal systems may be niches
- ***Crucible*** – extreme environments affect evolutionary paths

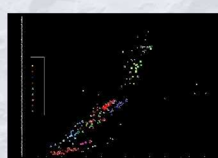
Impact craters

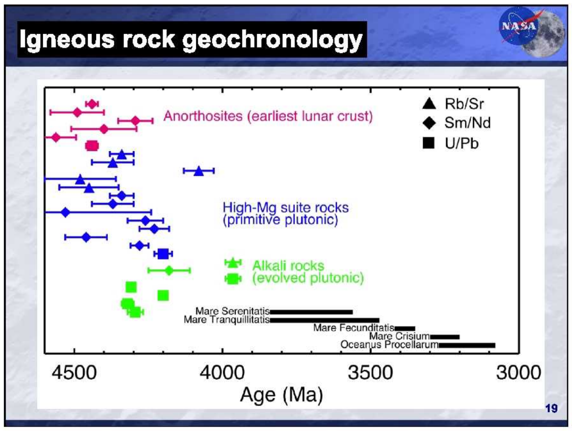
- Impact process is most akin to an explosion
- Impactor is vaporized, target is shocked

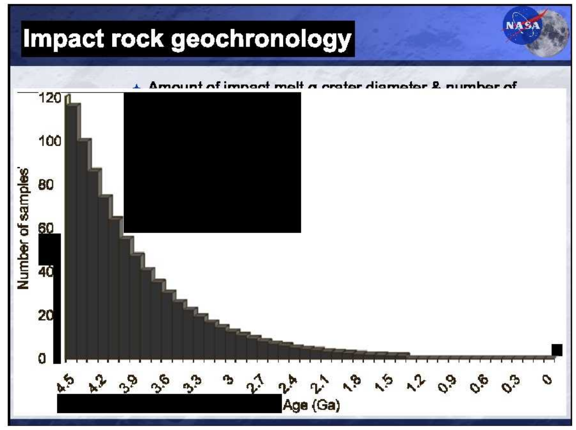
Energy = $1/2\ mv^2$
v = 11 km/s
for a 10-km rock,
$m = 10^{15}$ kg
$E = 10^{23}$ J
or
10^{7} Megatons TNT!

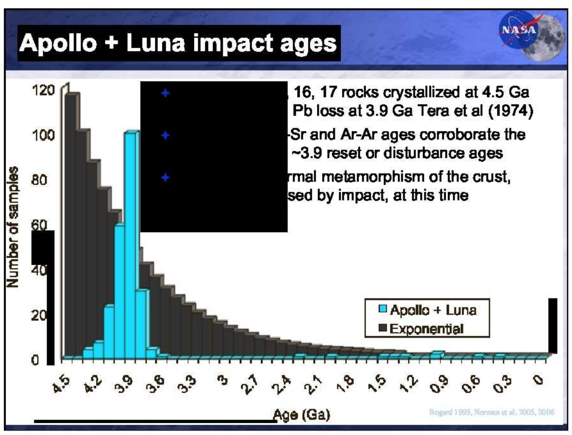
Impact melt rocks

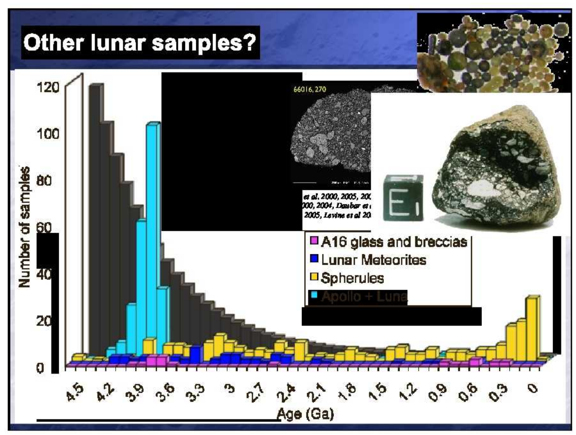
- Geologic association with specific craters and basins
- Form distinct groups in composition, texture, petrology
- Reflect distinct impactor composition that formed them

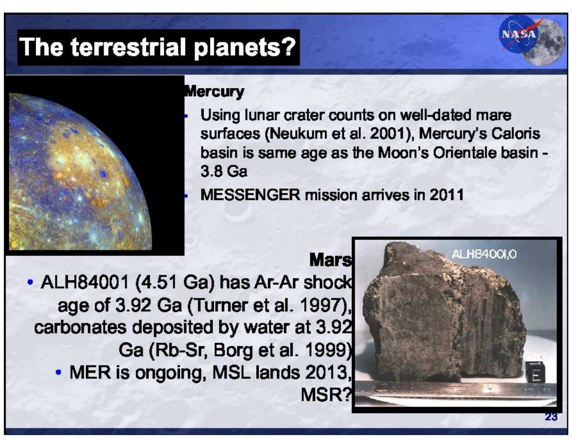


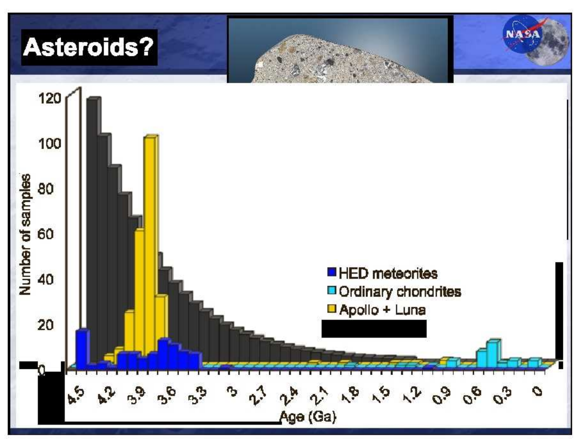

Igneous rock geochronology
Rb/Sr
Sm/Nd
U/Pb
Anorthosites (earliest lunar crust)
High-Mg suite rocks
(primitive plutonic)
Alkali rocks
(evolved plutonic)
Mare Serenitatis
Mare Tranquillitatis
Mare Fecunditatis
Mare Crisium
Oceanus Procellarum
4500
4000
3500
3000
Age (Ma)
19


Impact rock geochronology
[redacted]
Number of samples
120
100
80
60
40
20
0
4.5 4.2 3.9 3.6 3.3 3 2.7 2.4 2.1 1.8 1.5 1.2 0.9 0.6 0.3 0
Age (Ga)

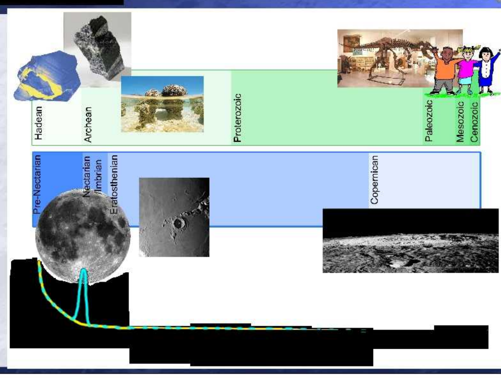

Apollo + Luna impact ages
[redacted] 16, 17 rocks crystallized at 4.5 Ga
[redacted] Pb loss at 3.9 Ga Tera et al (1974)
[redacted] Sr and Ar-Ar ages corroborate the
[redacted] ~3.9 reset or disturbance ages
[redacted] rmal metamorphism of the crust,
[redacted] sed by impact, at this time
Number of samples
120
100
80
60
40
20
0
Apollo + Luna
Exponential
4.5 4.2 3.9 3.6 3.3 3 2.7 2.4 2.1 1.8 1.5 1.2 0.9 0.6 0.3 0
Age (Ga)


Other lunar samples?
66016,270
A16 glass and breccias
Lunar Meteorites
Spherules
Number of samples
120
100
80
60
40
20
0
4.5 4.2 3.9 3.6 3.3 3 2.7 2.4 2.1 1.8 1.5 1.2 0.9 0.6 0.3 0
Age (Ga)


The terrestrial planets?
Mercury
Using lunar crater counts on well-dated mare surfaces (Neukum et al. 2001), Mercury's Caloris basin is same age as the Moon's Orientale basin - 3.8 Ga
MESSENGER mission arrives in 2011
Mars
ALH84001 (4.51 Ga) has Ar-Ar shock age of 3.92 Ga (Turner et al. 1997), carbonates deposited by water at 3.92 Ga (Rb-Sr, Borg et al. 1999)
MER is ongoing, MSL lands 2013, MSR?
ALH84001,0
23


Asteroids?
Number of samples
120
100
80
60
40
20
HED meteorites
Ordinary chondrites
Apollo + Luna
4.5 4.2 3.9 3.6 3.3 3 2.7 2.4 2.1 1.8 1.5 1.2 0.9 0.6 0.3 0
Age (Ga)

The Earth?



25

A dynamic early solar system

- Total mass necessary to create late lunar basins 10^{21}-10^{22} g
- Solar-system accretional leftover sweepup is rapid (100 Myr) (Morbidelli et al. 2001) and requires total leftover masses of 10^{23} -10^{28} g (i.e. masses of Vesta & Earth)
- Earth-Moon debris sweepup is also rapid, doesn't hit all inner planets
- Asteroid breakup (Zappala et al.1998) requires Ceres-sized body breakup, dynamically unlikely at 3.9 Ga, no family observed
- Jupiter & Saturn migration (Levison et al. 2001, 2005; Gomes et al. 2007) scatters icy planetesimals, resonances sweep through main belt
- 5th terrestrial planet (Chambers et al. 2002) between Mars and main belt becomes unstable after 600 Myr, scatters asteroids & hits the sun
- Close brush with another galaxy or massive object?
- ***The early solar system was a dynamic, violent place to be!***

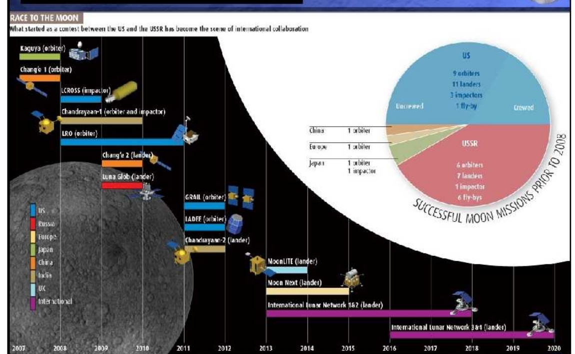
26

A Lunar Cataclysm…?

- Impact-melt sample groups tied to individual impact events based on major, minor, and trace elements, geologic interpretation
- Multiple different impact-melt groups from the Apollo landing sites are 3.9 Ga, tied to ***5 large basins*** plus other craters?
- Diverse approaches to further testing exist and are an opportunity for both the planetary and terrestrial communities
  - Understand sample ages and sample bias on planetary surfaces
  - Differences between the lunar surface and other locations
  - 3-D regolith modeling
- Pin down one large, old basin age – SPA Sample Return Mission

27

Robotic lunar missions

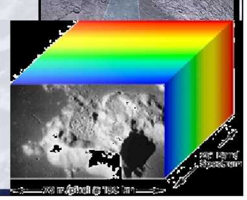


D. Mackenzie, New Scientist, July 11 2008

28

Moon Mineralogy Mapper (M3) and Mini-SAR (2008)

- US instruments aboard India's Chandrayaan-1 (just finished 10-month mission), managed under Discovery at MSFC
- **Mini-SAR objectives**:
  - Demonstrate active Synthetic Aperture Radar
  - Search for lunar polar ice
- **M3 Objectives**:
  - Global mineral maps
  - Investigate the possibility of water ice at the lunar poles

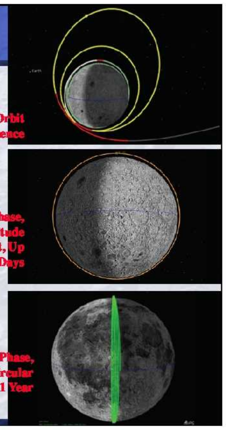


Lunar Reconnaissance Orbiter (2009)

- Lunar Reconnaissance Orbiter (LRO) – initiated in 2004 under the Vision for Space Exploration
- Exploration Systems Mission Directorate (ESMD) – focus is on datasets to help plan human activities
- Goddard project, managed under LPRP at MSFC
- **LRO Objectives:**
  - High-resolution imaging of the surface (50 cm / 20 inches)
  - High resolution maps of the Moon's surface addressing topography, temperature, lighting, and radiation
  - Assess the resources & environment of the Moon's polar regions

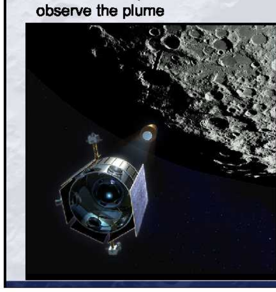
LRO Mission Overview

- On-board propulsion system used to capture at the Moon, insert into and maintain 50 km mean altitude circular polar reconnaissance orbit
- 1 year exploration mission followed by handover to NASA science mission directorate



LCROSS (2009)

- Lunar Crater Observation and Sensing Satellite, secondary payload on LRO vehicle, Ames project under LPRP management at MSFC
- Will use the expended LRO Centaur upper stage as an impactor and observe the plume

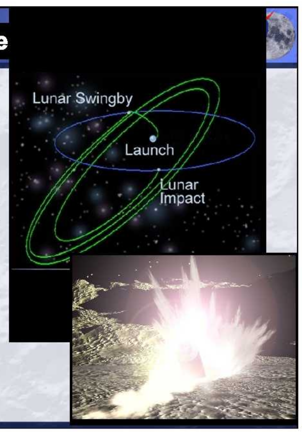


- **LCROSS Objectives:**
  - Confirm the presence or absence of water ice at a lunar pole
  - Create an ejecta plume and analyze it for the presence of water (ice and vapor), hydrocarbons and hydrated materials

32

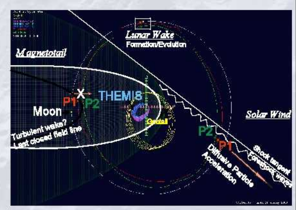
LCROSS Mission Ove

- About equal to 1.5 tons of TNT, excavating 200T lunar rock and soil
- Crater estimated to have ~20-25 m diameter and ~3 m depth
- Small by lunar standards - similar in size to East Crater at Apollo 11 landing site
- Impact site – Cabeus A at lunar south pole, impact date Oct. 8



ARTEMIS (2010)

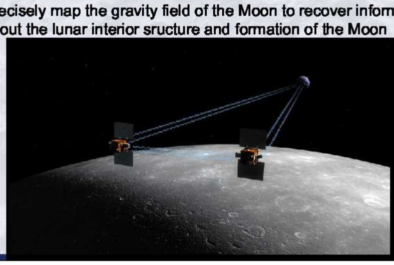
- Acceleration, Reconnection, Turbulence and Electrodynamics of Moon's Interaction with Sun
- Moves 2 Earth-observing THEMIS satellites into lunar orbits
- **ARTEMIS objectives**:
  - Study the lunar space environment, solar wind, magnetotail and lunar wake



34

GRAIL (2011)

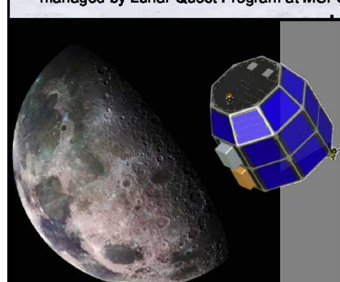
- Gravity Recovery and Interior Laboratory, an SMD PI-led mission by Dr. Maria Zuber at MIT, managed by Discovery program at MSFC
- Based on GRACE on the Earth - twin spacecraft with mutual ranging
- **GRAIL Objectives:**
  - Precisely map the gravity field of the Moon to recover information about the lunar interior sructure and formation of the Moon



35

LADEE (2012)

- Lunar Atmosphere, Dust and Environment Explorer, Ames/GSFC project, managed by Lunar Quest Program at MSFC

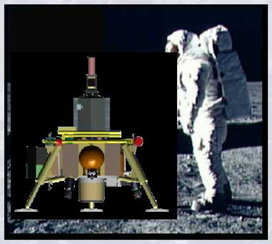


ADEE objectives:
Characterize the fragile lunar atmosphere before it is perturbed by further human activity
Determine if Apollo astronaut sightings were Na glow or dust
Document the dust environment to help guide engineering for the outpost and future robotic missions

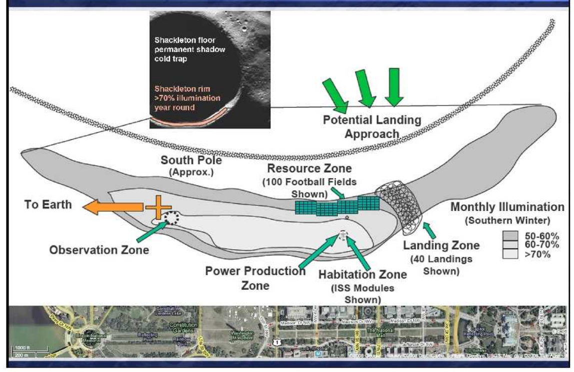
36

ILN Anchor Nodes (2018)

- International Lunar Network– a geophysical network to accomplish high priority science, but difficult for any single agency to accomplish on its own
- US and international landed missions, 2-4 US Landers planned, project at MSFC/APL, managed by Lunar Quest Program at MSFC
- **ILN Objectives:**
  - Understand the interior structure and composition of the moon
  - Determine the thickness of the crust, mantle, and core
  - Characterize the thermal state of the interior



Human landings (2020)



Summary

The Moon is a cornerstone for all rocky planets

- The Moon is a ***terrestrial*** body, formed and evolved similarly to Earth, Mars, Mercury, Venus, and large asteroids
- The Moon is a ***differentiated*** body, with a layered internal structure (crust, mantle, and core)
- The Moon is a ***cratered*** body, preserving a record of bombardment history in the inner solar system
- The Moon is an ***active*** body, experiencing moonquakes, releasing primordial heat, conducting electricity, sustaining bombardment, and trapping volatile molecules

Lunar robotic missions provide early science return to obtain important science and engineering objectives, rebuild a lunar science community, and keep our eyes on the Moon

39